

# Beam Dump problem and Neutrino Factory Based on a $e^+e^-$ Linear Collider

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## Abstract

The beam of an  $e^+e^-$  Linear Collider after a collision at the main interaction point can be utilized to construct the neutrino factory with exceptional parameters. We also discuss briefly possible applications of some elements of the proposed scheme to standard fixed target experiments and new experiments with  $\nu_\mu N$  interactions.

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## 1. Introduction

The projects of the  $e^+e^-$  Linear Collider (LC) – ILC, CLIC, ... – contain one essential element that is not present in other colliders. Here each  $e^-$  (or  $e^+$ ) bunch will be used only once, and physical collisions retain two very dense and strongly collimated beams of high energy electrons with the precisely known time structure. We consider, for definiteness, electron beam parameters of the ILC project [1]:

$$\begin{aligned} &\text{particle energy } E_e = 250 \div 500 \text{ GeV,} \\ &\text{number of electrons per second } N_e \sim 10^{14}/\text{s,} \\ &\text{transverse size and angular spread are negligible;} \\ &\text{time structure is complex and precisely known.} \end{aligned} \tag{1}$$

The problem of dealing with this powerful beam dump is under extensive discussions, see, e.g., [1].

About 10 years ago we suggested to utilize such used beams in project TESLA to initiate operation of a subcritical fission reactor and to construct a neutrino factory ( $\nu F$ ) [2, 3]. With new studies of ILC and CLIC, these proposals should be renewed.

- Neutrino factories promise to solve many problems. The existing projects (see, e.g., [4]-[6]) are very expensive, their physical potential is limited by an expected neutrino energy and productivity of a neutrino source.

The proposed  $\nu F$  based on LC is much less expensive than those discussed nowadays since there are no additional costs for construction of a high intensity and high energy particle source. The combination of the high number of particles in the beam and high particle energy with precisely known time structure (1) provides very favorable properties of such a  $\nu F$ . The initial beam will be prepared in LC irrelevantly to the  $\nu F$  construction. The construction demands no special electronics except that for detectors. The initial beam is very well collimated, therefore the additional efforts for beam cooling are not necessary. Use of the IceCube in Antarctica or Lake Baikal detector just as specially prepared detector not so far from LC as a far distance detector (FDD) allows to study in details  $\nu_\mu - \nu_\tau$  oscillations and observe possible oscillations  $\nu_\mu \rightarrow \nu_{sterile}$  (in latter case – via a measurement of deficit of  $\nu_\mu N \rightarrow \mu X$  events).

The neutrino beam will have a very well known discrete time structure that repeats the same structure in the LC. This fact allows one to separate cosmic and similar backgrounds during operation with high precision. A very simple structure of a neutrino generator allows to calculate the energy spectrum and a content of the main neutrino beam with high accuracy. It must be verified with high precision in a nearby detector (NBD).

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In this project an incident neutrino beam will contain mainly  $\nu_\mu$ ,  $\bar{\nu}_\mu$  with a small admixture of  $\nu_e$  and  $\bar{\nu}_e$  and tiny dose of  $\nu_\tau$  and  $\bar{\nu}_\tau$  (the latter can be calculated with low precision). For the electron beam energy of 250 GeV, neutrino energies are spread up to about 80 GeV with the mean energy of about 30 GeV, providing reliable observation of  $\tau$ , produced by  $\nu_\tau$  from the  $\nu_\mu - \nu_\tau$  oscillations. In the physical program of a discussed vF we consider only the problem of  $\nu_\mu - \nu_\tau$  and/or  $\nu_\mu - \nu_{sterile}$  oscillations. The potential of this vF in solving other problems of  $\nu$  physics should be studied after detailed consideration of the project, see also [6].

## 2. Elements of neutrino factory. Scheme

The proposed scheme deals with the electron beam used in LC and contains the following parts, Fig. 1:

- Beam bending magnet (BM).
- Pion producer (PP),
- Neutrino transformer (NT),
- Nearby detector (NBD),
- Far distance detector (FDD).

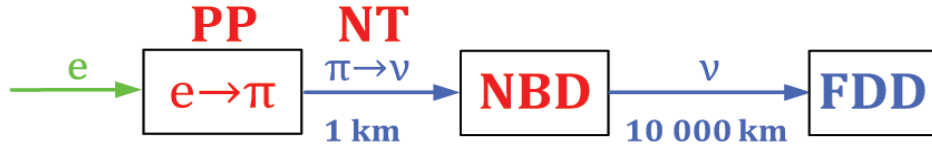


Figure 1: Main parts of the neutrino factory after BM.

## 3. Beam bending magnet

The system should start with a bending magnet situated after the detector of the basic collider. It turns the used beam at an angle necessary to reach FDD by sacrificing monochromaticity but without essential growth of the angular spread. The vertical component of the turning angle  $\alpha_V$  is determined by Earth curvature. Let us denote the distance from LC to FDD at the Earth surface by  $L_F$ . To reach FDD, the initial beam (and therefore NT) should be turned before PP at the angle  $\alpha_V = L_F / (2R_E)$  below horizon (here  $R_E$  is the Earth radius).

The horizontal component of turning angle can be minimized by a suitable choice of the proper LC orientation (orientation of an incident beam near the LC collision point).

## 4. Pion producer (PP)

The PP can be, for example, a 20 cm long water cylinder (*one radiation length*). Water in the cylinder can rotate for cooling. In this PP almost each electron will produce a bremsstrahlung photon with energy  $E_\gamma = 100 - 200$  GeV. The angular spread of these photons is roughly the same as that of the initial beam ( $\sim 0.1$  mrad). Bremsstrahlung photons have an additional angular spread of about  $1/\gamma \approx 2 \cdot 10^{-6}$ . These two spreads are negligible for our problem.

Then these photons collide with nuclei and produce pions,

$$\gamma N \rightarrow N' + \pi' s, \quad \sigma \approx 110 \mu b. \quad (2)$$

This process gives about  $10^{-3}$   $\gamma N$  collisions per one electron that corresponds to about  $\sim 10^{11}$   $\gamma N$  collisions per second. On average, each of these collisions produces a single pion with high energy  $E_\pi > E_\gamma/2$  (for estimates  $\langle E_\pi^h \rangle = 70$  GeV) and at least 2-3 pions with lower energy (for estimates,  $\langle E_\pi^\ell \rangle \approx 20$  GeV).

Mean transverse momentum of these pions is 350-500 MeV. The angular spread of high energy pions with the energy  $\langle E_\pi^h \rangle$  is within 7 mrad. Increase of the angular spread of pions with decrease of energy is compensated by growth of the number of produced pions. Therefore, for estimates we accept that the pion flux within an angular

interval of 7 mrad contains  $\sim 10^{11}$  pions with  $E_\pi = \langle E_\pi^h \rangle$  and the same number of pions with  $E_\pi = \langle E_\pi^\ell \rangle$  per second. Let us denote the energy distribution of pions flying almost forward by  $f(E)$ .

- Certainly, more refined calculations should also consider production and decay of  $K$  mesons etc.
- The production of  $\nu_\tau$  in the reaction mentioned in ref. [8]

$$\gamma N \rightarrow D_s^\pm X \rightarrow \nu_\tau \bar{\tau} X. \quad (3a)$$

plays the most essential role for our estimates. Its cross section rapidly increases with energy growth and

$$\sigma(\gamma N \rightarrow \tau + \dots) \approx 2 \cdot 10^{-33} \text{ cm}^2 \text{ at } E_\gamma \approx 50 \text{ GeV}. \quad (3b)$$

## 5. Neutrino transformer (NT). Neutrino beams

For the neutrino transformer (NT), we suggest a high vacuum beam pipe of length  $L_{NT} \approx 1$  km and radius  $r_{NT} \approx 2$  m. Here muon neutrino  $\nu_\mu$  and  $\bar{\nu}_\mu$  are created from  $\pi \rightarrow \mu \nu$  decay. This length  $L_{NT}$  allows that more than one quarter of pions with  $E_\pi \leq \langle E_\pi^h \rangle$  decay. The pipe with a radius  $r_{NT}$  gives an angular coverage of 2 mrad, which cuts out 1/12 of the total flux of low and medium energy neutrinos. With the growth of pion energy, two factors act in opposite directions. First, the initial angular spread of pions decreases with this growth, therefore, the fraction of the flux selected by the pipe will increase. Second, the number of pion decays within a relatively short pipe decreases with this growth. These two tendencies compensate each other in the resulting flux.

The energy distribution of neutrinos obtained from the decay of a pion with the energy  $E$  is uniform in the interval  $(aE, 0)$  with  $a = 1 - (m_\mu/m_\pi)^2$ . Therefore, the distribution  $F(\varepsilon)$  of the neutrino energy  $\varepsilon$  can be obtained from the energy distribution of pions near the forward direction  $f(E)$  as

$$F(\varepsilon) = \int_{\varepsilon/a}^{E_e} f(E) dE / (aE), \quad a = 1 - \frac{m_\mu^2}{m_\pi^2} \approx 0.43. \quad (4)$$

The increase of the angular spread in the decay is negligible in the rough approximation. Finally, at the end of NT we expect to have the neutrino flux within the angle of 2 mrad

$$\begin{aligned} & 2 \cdot 10^9 \text{ v/s with } E_\nu = \langle E_\nu^h \rangle \approx 30 \text{ GeV}, \\ & \text{and } 2 \cdot 10^9 \text{ v/s with } E_\nu = \langle E_\nu^\ell \rangle \approx 9 \text{ GeV}. \end{aligned} \quad (5)$$

We denote below neutrinos with  $\langle E_\nu \rangle = 30$  GeV and 9 GeV as *high energy neutrinos* and *low energy neutrinos*, respectively.

- Other sources of  $\nu_\mu$  and  $\nu_e$  change these numbers only slightly.

### • The background $\nu_\tau$ beam.

The  $\tau$  neutrino are produced in PP. Two mechanisms were discussed in this respect, the Bethe-Heitler process  $\gamma N \rightarrow \tau \bar{\tau} + X$  [7] and the process (3) which is dominant [8]. The cross section (3) is five orders smaller than  $\sigma(\gamma N \rightarrow X)$ . The mean transverse momentum  $\langle p_t \rangle$  of  $\nu_\tau$  is given by  $m_\tau$ , it is more than three times higher than  $\langle p_t \rangle$  for  $\nu_\mu$ . Along with, e.g.,  $\bar{\nu}_\tau$  produced in this process, in NT each  $\tau$  decays to  $\nu_\tau$  plus other particles. Therefore, each reaction of such a type is a source of a  $\nu_\tau + \bar{\nu}_\tau$  pair. Finally, for the flux density we have

$$N_{\nu_\tau} \sim 3 \cdot 10^3 \text{ v}_\tau / (\text{s} \cdot \text{mrad}^2) \lesssim 8 \cdot 10^{-6} N_{\nu_\mu}. \quad (6)$$

The  $\nu_\tau$  (or  $\bar{\nu}_\tau$ ) energy is typically higher than that of  $\nu_\mu$  by a factor of  $2 \div 2.5$ .

Besides,  $\nu_\tau$  will be produced by non-decayed pions within the protecting wall behind NP in the process like  $\pi N \rightarrow D_s X \rightarrow \tau \nu_\tau X$ . The cross section of this process increases rapidly with the energy growth and equals  $0.13 \mu\text{b}$  at  $E_\pi = 200$  GeV [9]. A rough estimate shows that the number of additional  $\nu_\tau$  propagating in the same angular interval is close to the estimate (6). In the numerical estimates below we consider, for definiteness, the first contribution only. A measurement of  $\nu_\tau$  flux in the NBD is a necessary component for the study of  $\nu_\mu - \nu_\tau$  oscillations in FDD.

## 6. Nearby detector (NBD)

The main goal of the nearby detector (NBD) is to measure the energy and angular distribution of neutrinos within the beam as well as  $N_{\nu_e}/N_{\nu_\mu}$  and  $N_{\nu_\tau}/N_{\nu_\mu}$ .

We propose to place the NBD at the reasonable distance behind NT and a concrete wall (to eliminate pions and other particles from the initial beam). For estimates, we consider the body of NBD in a form of the water cylinder with a radius about 2-3 m (roughly the same as NT) and length  $\ell_{NBD} \approx 100$  m. The detailed construction of the detector should be considered separately.

For  $E_\nu = 30$  GeV, the cross section for  $\nu$  absorption is

$$\begin{aligned}\sigma(\bar{\nu}N \rightarrow \mu^+h) &= 0.1\pi\alpha^2 \frac{m_p E_{\bar{\nu}}}{M_W^4 \sin^4 \theta_W} \approx 10^{-37} \text{cm}^2, \\ \sigma(\nu N \rightarrow \mu^-h) &= 0.22\pi\alpha^2 \frac{m_p E_\nu}{M_W^4 \sin^4 \theta_W} \approx 2 \cdot 10^{-37} \text{cm}^2.\end{aligned}\tag{7}$$

Taking into account these numbers, the free path length in water is  $\lambda_{\bar{\nu}} = 10^{13}$  cm and  $\lambda_\nu = 0.45 \cdot 10^{13}$  cm. That gives

$$\begin{aligned}(1 \div 2) \cdot 10^7 \text{ } \mu/\text{year} \text{ (with } \langle E_\mu \rangle \sim 30 \text{ GeV);} \\ 150 \div 250 \text{ } \tau/\text{year} \text{ (with } \langle E_\tau \rangle \sim 50 \text{ GeV)}.\end{aligned}\tag{8}$$

(here 1 year =  $10^7$  s, that is LC working time). These numbers look sufficient for detailed measurements of muon neutrino spectra and for verification of the calculated direct  $\nu_\tau$  background.

## 7. Far Distance Detector (FDD)

Here we consider how the FDD can be used for a solution of the single problem:  $\nu_\mu - \nu_\tau$  and (or)  $\nu_\mu - \nu_{sterile}$  oscillations. Other possible applications should be considered elsewhere. We discuss here two possible position of FDD – at relatively small distance from LC – FDD I (with special detector) and very far from LC – FDD II (with using big detectors, constructed for another goals).

For the length of oscillations we use estimate [10]

$$L_{osc} \approx E_\nu / (50 \text{ GeV}) \cdot 10^5 \text{ km}.\tag{9}$$

### 7.1. FDD I

We discuss first the opportunity to construct special relatively compact detector with not too expensive excavation work at the distance of a few hundred kilometers from LC (for definiteness, 200 km). For this distance the NT should be turned at 16 mrad angle below horizon. This angle can be reduced by 3 mrad (one half of angular spread of initial pion beam).

We consider the body of this FDD in the form of water channel of length 1 km with radius  $R_F \approx 40$  m. The transverse size is limited by water transparency.

The fraction of neutrino's reaching this FDD is given by ratio  $k = (R_F/L_F)^2 / [(r_{NT}/L_{NT})^2]$ . In our case  $k \approx 0.01$ . Main effect under interest here is  $\nu_\mu \rightarrow \nu_\tau$  oscillation. They add  $(L_F/L_{osc})^2 N_{\nu_\mu}$  to initial  $N_{\nu_\tau}$ .

In FDD of chosen sizes we expect the counting rate to be just 10 times lower than that in NBD (8) for  $\nu N \rightarrow \mu X$  reactions with high energy neutrino. We also expect the rate of  $\nu_\tau N \rightarrow \tau X$  events to be another  $10^5$  times lower (that is about 10 times higher than the background given by initial  $\nu_\tau$  flux),

$$\begin{aligned}N(\nu_\mu N \rightarrow \mu X) &\approx (1 \div 2) \cdot 10^6/\text{year}, \\ N(\nu_\tau N \rightarrow \tau X) &\approx (10 \div 20)/\text{year}\end{aligned}\text{ in FDDI}.\tag{10}$$

For neutrino of lower energies effect increases. Indeed,  $\sigma(\nu N \rightarrow \tau X) \propto E_\nu$  while  $L_{osc} \propto E_\nu$ . Therefore, observed number of  $\tau$  from oscillations increases  $\propto 1/E_\nu$  at  $E_\nu \geq 10$  GeV. The additional counting rate for  $\nu_\tau N \rightarrow \tau X$  reaction with low energy neutrino (with  $\langle E_\nu \rangle = 9$  GeV) cannot be estimated so simply, but rough estimates give numbers similar to (10).

These numbers look sufficient for separation of  $\nu_\mu - \nu_\tau$  oscillations and rough measurement of  $s_{23}$ .

Note that at considered FDD I size the counting rate of  $\nu_\tau N \rightarrow \tau X$  reaction is independent on FDD distance from LC,  $L_F$ . The growth of  $L_F$  improves the signal to background ratio for oscillations. The value of signal naturally increases with growth of volume of FDD I.

## 7.2. FDD II

Now we consider very attractive opportunity to use for FDD existent neutrino telescope with volume of 1 km<sup>3</sup> situated at Lake Baikal or in Antarctica (IceCube detector) with the distance *basic LC — FDD II*  $L_F \approx 10^4$  km. This opportunity requires an excavation work for NT and NBD at the angle about 50° under horizon.

At this distance according to (9) for  $\nu$  with energy about 30 GeV, we expect the conversion of  $(L_F/L_{osc})^2 \approx 1/36$  for  $\nu_\mu \rightarrow \nu_\tau$  or  $\nu_\mu \rightarrow \nu_{sterile}$ .

The number of expected events  $\nu_\mu \rightarrow \mu X$  with high energy neutrinos will be about 0.01 of that in NBD,

$$\begin{aligned} N(\nu_\mu N \rightarrow \mu X) &\approx (1 \div 2) \cdot 10^5/\text{year}, \\ N(\nu_\tau N \rightarrow \tau X) &\approx 3 \cdot 10^3/\text{year}. \end{aligned} \quad (11)$$

The contribution of low energy neutrinos increases both these counting rates.

Therefore, one can hope that a few years of experimentation with a reasonable  $\tau$  detection efficiency will allow one to measure  $s_{23}$  with percent accuracy, and a similar period of observation of  $\mu$  production will allow to observe the loss of  $\nu_\mu$  due to transition of this neutrino to  $\nu_{sterile}$ .

## 8. Discussion

Here we suggest to construct Neutrino Factory with great physical potential using beam of Linear Collider after main collision there.

All technical details of the proposed scheme including sizes of all elements, construction, and materials of detectors can be modified in the forthcoming simulations and optimization of parameters. The numbers obtained above represent the first careful estimates. In particular, rate of neutrino can be enhanced with increasing of length of PP, this rate can appear significantly higher after more accurate calculation of pion production there, the length of NT can be reduced due to economical reasons, etc.

After first stage of Linear Collider its energy can be increased. For these stages proposed scheme can be used without changes (except magnetic field in BM and taking into account new time structure of neutrino beam).

We did not discuss here methods of  $\mu$  and  $\tau$  detection and their efficiency. Next, a large fraction of residual electrons, photons and pions leaving the PP will reach the walls of the NT pipe. The heat sink and radiation protection of this pipe must be taken into account.

A more detailed physical program of this vF will include many features of that in other projects (see, e.g., [4]–[6]).

## 9. Other possible applications of some parts of vF

• **PP for the fixed target experiment.** The PP can be treated as an  $eN/\gamma N$  collider with luminosity  $3 \cdot 10^{39} \text{ cm}^{-2} \text{ s}^{-1}$  with a c.m.s. energy of about 23 GeV. Therefore, if one adds some standard detector equipment behind PP, it can be also used for a fixed target  $eN/\gamma N$  experiment. Here one can study rare processes in  $\gamma N$  collisions,  $B$  physics, etc.

• **Additional opportunity for using NBD.** The high rate of  $\nu_\mu N \rightarrow \mu X$  processes expected in NBD allows one to study new problems of high energy physics. The simplest example is the opportunity to study charged and axial current induced structure functions and diffraction ( $\nu N \rightarrow \mu + \text{hadrons}$ ,  $\nu N \rightarrow \mu N' \rho^\pm$ ,  $\nu N \rightarrow \mu N' b_1^\pm, \dots$ ) with high precision.

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